(Micro/)Nanoscale Networks for a New World

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Seminar Summary

Nanonetworks

Re-define *Communication Network* for micro/nanoscale $(10^{-6}/10^{-9}\text{m})$

Communications Modeling

Same toolbox, different problems

Biophysical Signals

Can we understand and control signaling in “small” natural systems?

1. **Background (20 min)**
    - Communications Engineering and Networks
    - Nanonetworking and Molecular Communication
    - Applications
2. **Communications Modeling and Analysis (15 min)**
    - Micro/Nano Channel Modeling
    - Communications and Networking Solutions
3. **Biophysical Signal Propagation (10 min)**
    - Simulation Tools
    - Behavioral Dynamics
    - Information Transfer
4. **Conclusions**

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- **Destination** – Where information is read

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2. How to represent the information in a signal?
3. What happens to the signal as it propagates?
4. How to detect the signal?
5. How to recover the information from the signal?

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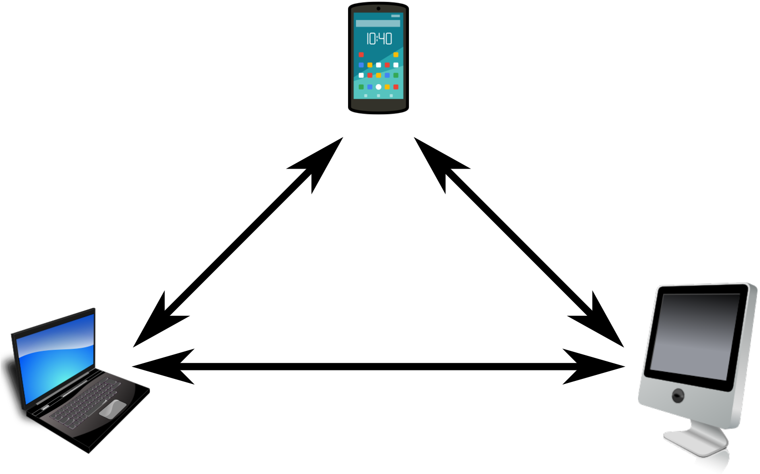
How good are we at each step?

What are Communication Networks?

Each “device” could be both a transmitter and receiver



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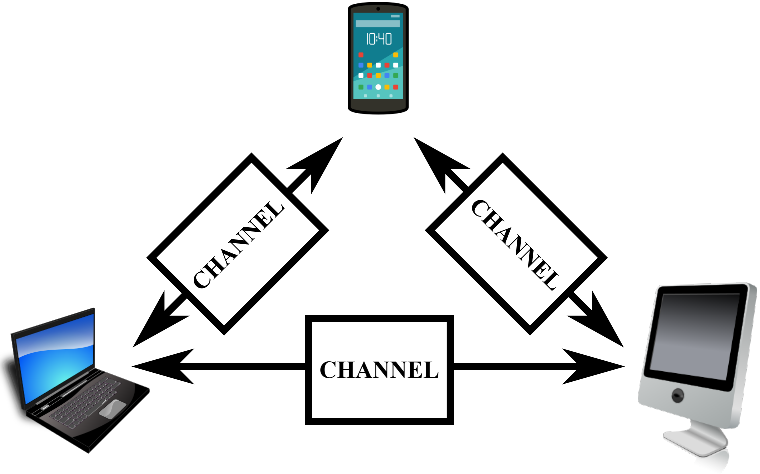

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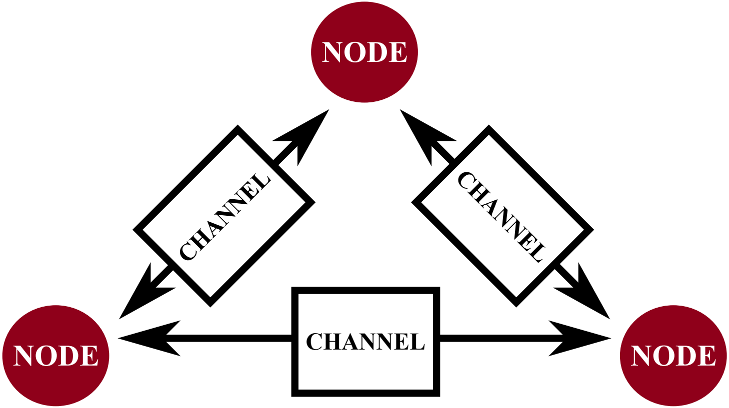

Towards Nanonetworks

Imagine tiny networks with many thousands of devices

- Simple devices cooperating to complete challenging tasks
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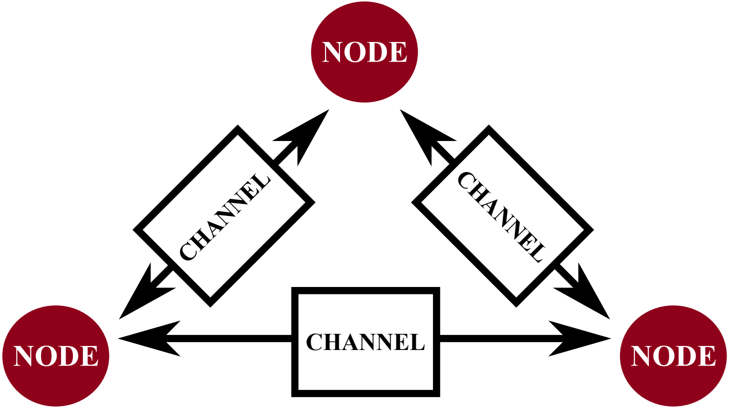
Is this a hopeless fantasy or current reality?

Richard Feynman, Caltech, 1959

“There’s Plenty of Room at the Bottom”

Can we Re-Conceptualize What a Network Is?



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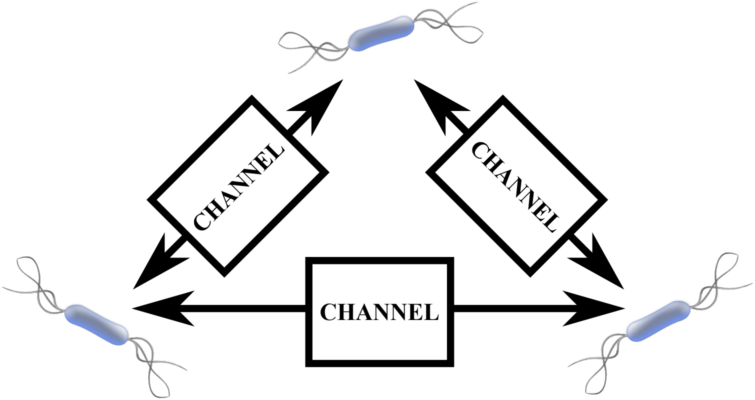


Micro/Nanonetworks

Nanonetworks

A communication network using devices (*nanomachines*) with *nanoscale functional components*

Why do we Need Nanonetworks?

Devices are relatively simple and cannot do much on their own

Why Micro/Nano?

Many devices with nanoscale components are *microscale* in size

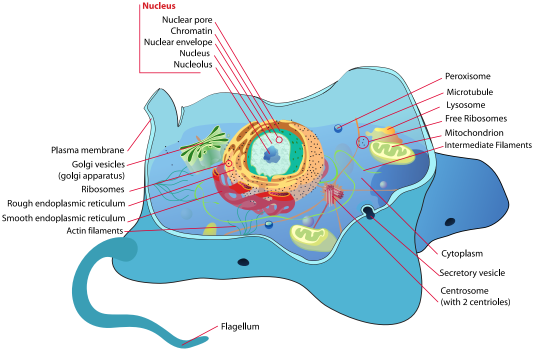
How Big is a Nanomachine?

What objects are on the order of a nanometre in size?

- Biological cells – most between $1\,\mu$m and $100\,\mu$m
- Single atoms – under 1 nm in diameter
- “Small” molecules – about 1 nm
- Proteins – $5 - 10$ nm
- Viruses – on the order of 100 nm
- Cellular Organelles (subunits) – 25 nm $-1\,\mu$m

A nice visual resource: `http://scaleofuniverse.com/`

What Can a Single Nanomachine Do?



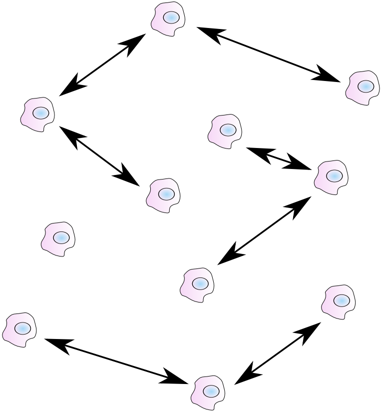
An Animal Cell
Source: Wikimedia Commons

Cells can be very complex structures

- Food Processing, Mobility, Reproduction, Sensing
- **Communication**

Cooperation: Making it Happen

Single nanomachines may be complex but limited output

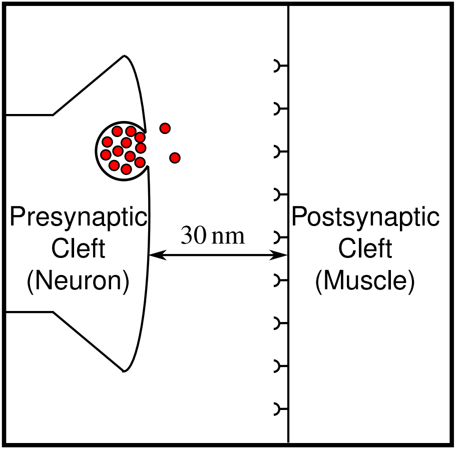


Network of Communicating Cells

- A **Nanonetwork** is the interconnection of nanomachines
- Cooperate to perform more complex tasks
- Share different local information

Examples of Natural Nanonetworks

Neuromuscular Junction



Neurons control muscle contraction

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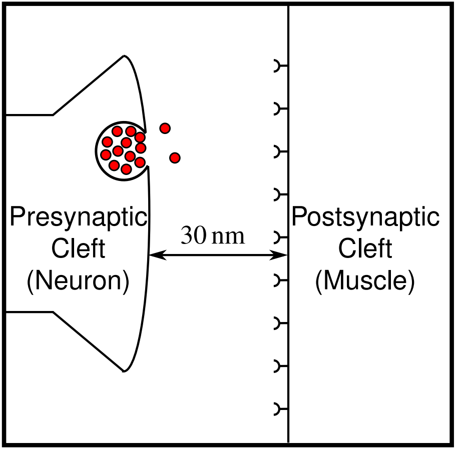

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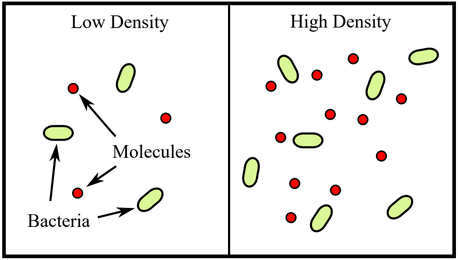
Quorum Sensing



Bacteria estimate population density

Nanonetworking for Communications Engineers

We want communication systems that are:

- **Reliable** - low probability of receiver error
- **Realistic** - achievable with current/future technology
- **Really fast** - transmit as much data as possible

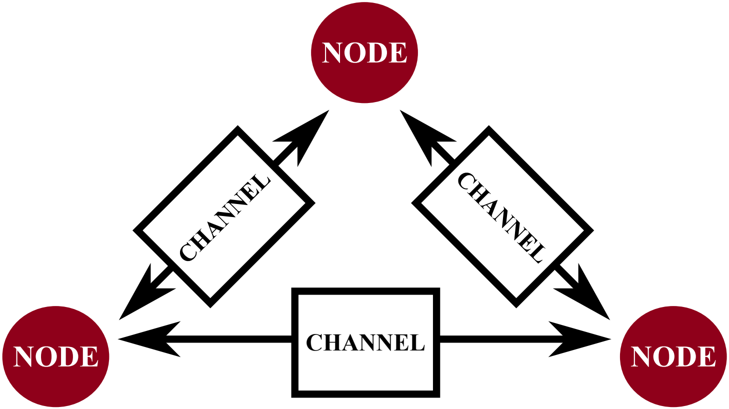
Aim of Communication Analysis

Robust network design that is not application-specific but does consider the envisioned capabilities of nanomachines

- Conventional problem still exists - transmission of information

Nanonetworking Channels

Can our nodes be nanomachines? What does this change?



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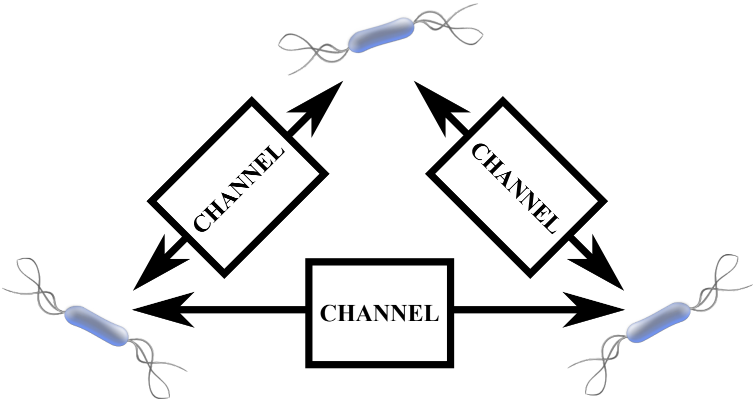


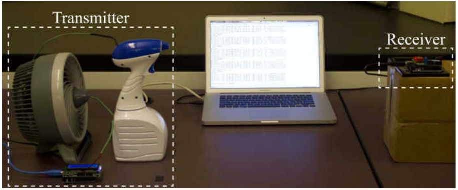
How to Build the Network?

Two main streams of nanonetwork design consider using either:

1. **Electromagnetic Radiation** - a somewhat top-down design approach
2. **Molecular Communication** - use molecules as information carriers

Molecular communication is a more natural choice for biologically-based nanomachines

Tabletop Signaling[1]



[1] Farsad, Guo, Eckford, *Proc. IEEE INFOCOM Workshops*, Apr. 2014

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Molecular Communication Experiments

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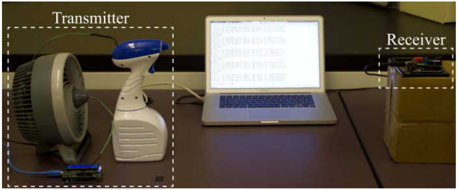

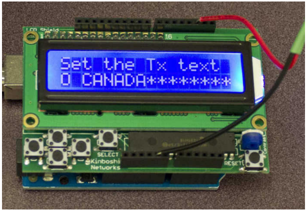

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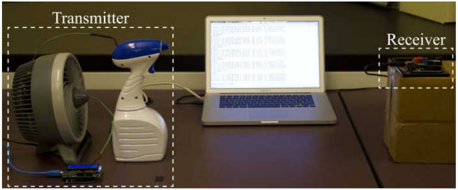
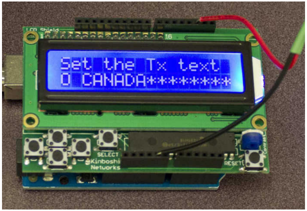
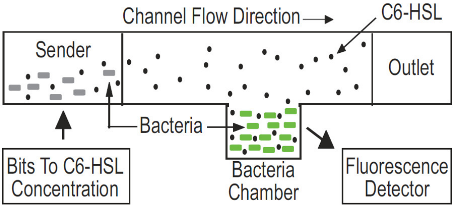




Using Bacteria as Transceivers[2]



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Molecular Communication Advantages

Molecular communication presents the following advantages:

- **Feasibility** – Regarded as easier to implement than other approaches in the near term,
- **Scale** – Appropriate size for nanomachines
- **Bio-compatibility** – Integration with living systems possible (though not guaranteed!)
- **Energy Efficiency** – Biochemical reactions have high efficiencies
- **Functional Complexity** – Billions of years of evolution

Other advantages depend on the particular implementation

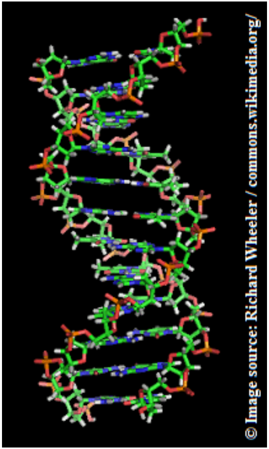
Molecular Communication Challenges

Molecular communication presents the following challenges:

- **Stochasticity** – Random propagation of molecules, environmental noise
- **Delay** – Propagation times very long compared to speed of light
- **Range** – Techniques can have very short practical ranges
- **Fragility** – Biological components can be environmentally sensitive (temperature, pH, other reagents)

Biomedical Applications

- **Targeted drug delivery** – Cooperatively release medication
- **Health monitoring** – *in vivo* diagnostics
- **Lab-on-a-chip** – Drug development and discovery
- **Regenerative medicine** – Rebuild damaged tissues, organs
- **Genetic engineering** – Manipulate DNA



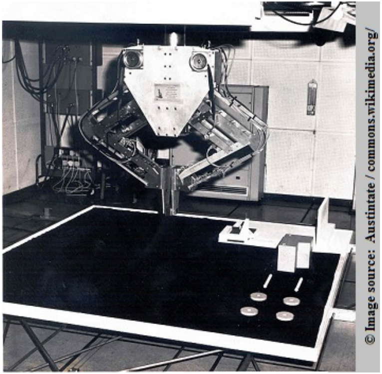
DNA Double-Helix

Environmental Applications

- **Environmental monitoring** – Detection of pollutants or toxins
- **Degradation** – Safe conversion of undesired materials

Manufacturing Applications

- **Chemical reactors** – Optimize production
- **Quality control** – Identification of product defects
- **Bottom-up formation** – Precise construction of components
- **New functionality** – Integrate nanonetworks into new products



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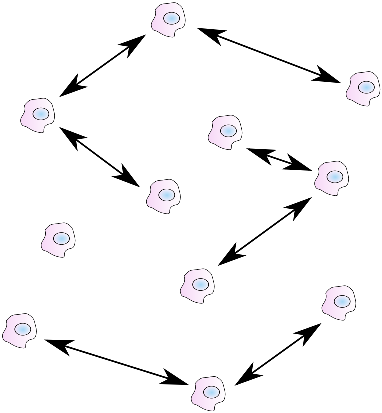
Modeling a Nanonetwork



How to characterize a nanonetwork?

Can we take ideas from modern communications engineering?

Overview of Channel Modeling

The Channel Modeling Problem

Mathematically describe what happens to signals between TX and RX

Diffusion

Many molecule collisions → random behavior

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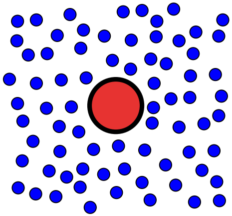

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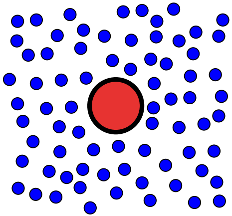

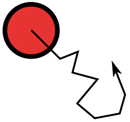

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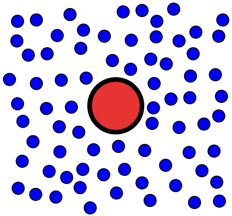

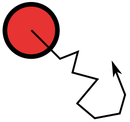

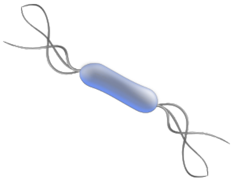

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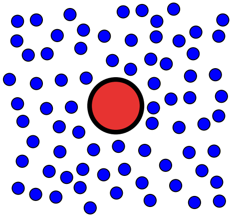

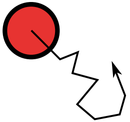

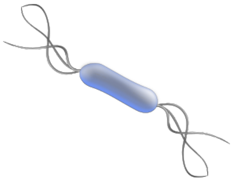

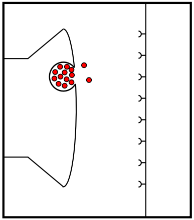

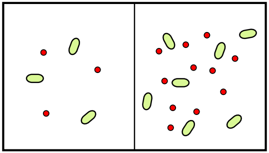

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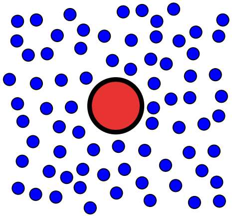
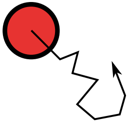
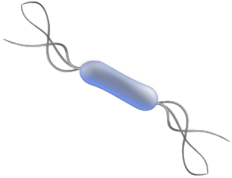
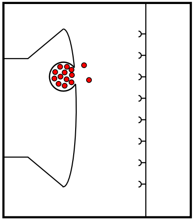








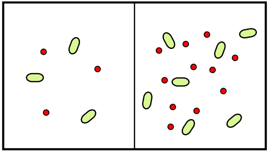
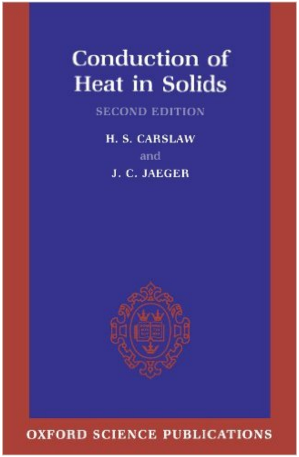


Photo: Wikimedia (CC BY-SA 3.0) `https://commons.wikimedia.org/wiki/File:Euphydryas_editha_5679.JPG`

Mathematics of Diffusion

Solving partial differential equations



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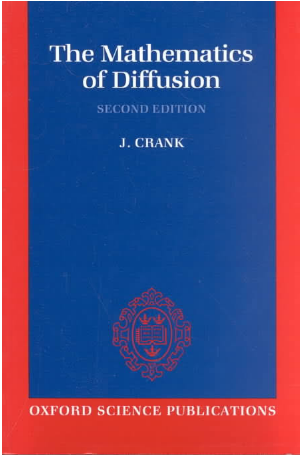

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Diffusion Curves

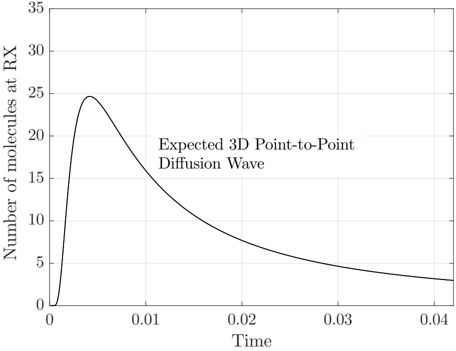
Describing expected behavior

TX

RX

Expected “point-to-point”channel response:

$$\overline{N}_{\mathrm{RX}}(t) = \frac{N V_{\mathrm{RX}}}{(4\pi D t)^{3/2}} \exp\left(-\frac{d^2}{4Dt}\right)$$



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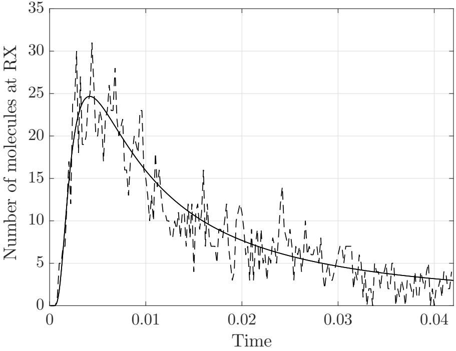
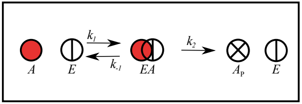
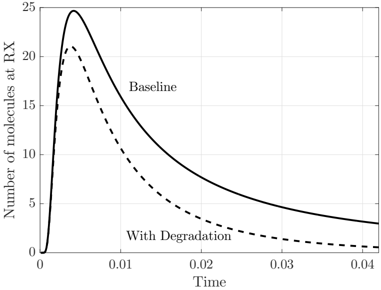


Molecule Degradation[1]





[1]Noel, Cheung, Schober, *IEEE Trans. NanoBiosci.*, Mar. 2014

[2]Noel, Cheung, Schober, *IEEE Trans. NanoBiosci.*, Sept. 2014

Enhanced Diffusion

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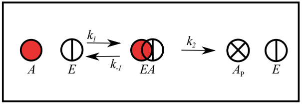
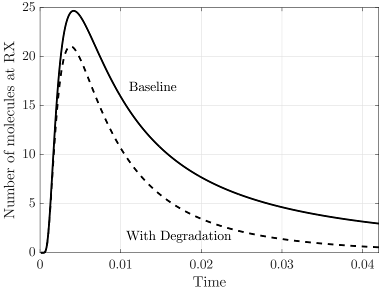
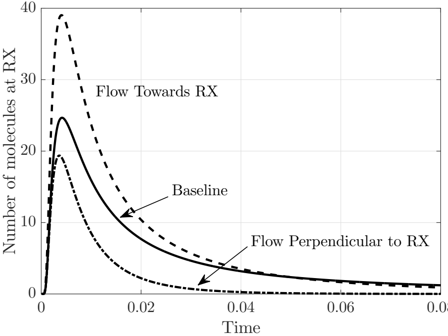




Bulk Fluid Flow[2]



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Channel Models with Active Receivers

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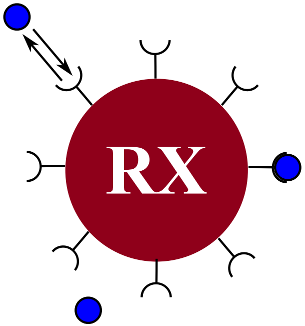

[1] Deng, Noel, Elkashlan, Nallanathan, Cheung, *IEEE Trans. Mol. Biol. Multi-Scale Commun.*, Dec. 2015

[2] Lu, Higgins, Noel, Leeson, Chen, *IEEE Trans. NanoBiosci.*, Dec. 2016

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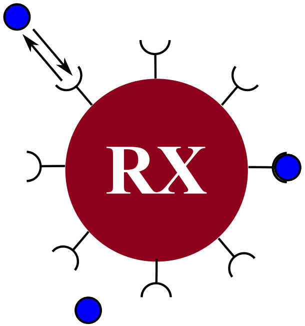
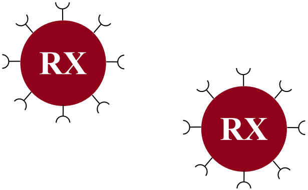


Multiple Absorbers[2]



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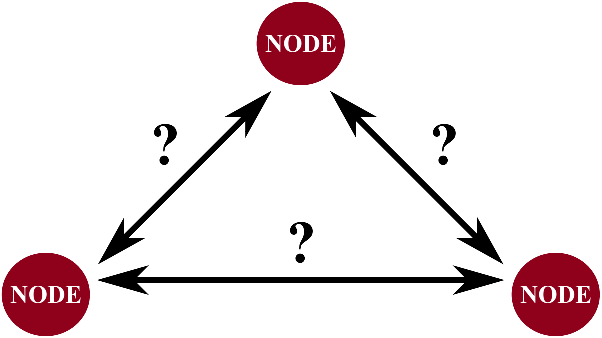
Communications Analysis Overview

Single Link

Communications Analysis Overview

Single Link

Multiple Links (Network)



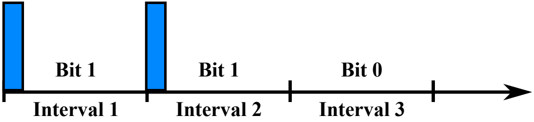
Our Communication Problem

How reliably can we send information using diffusion?

MESSAGE → TX → ENVIRONMENT → RX → DESTINATION

Our Communication Problem

How reliably can we send information using diffusion?



Our Communication Problem

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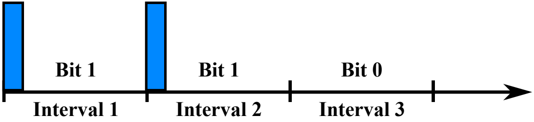
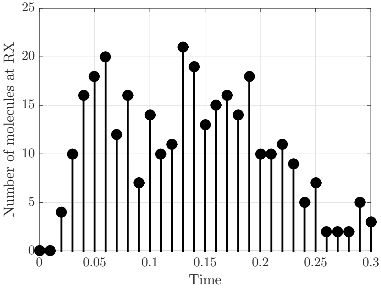




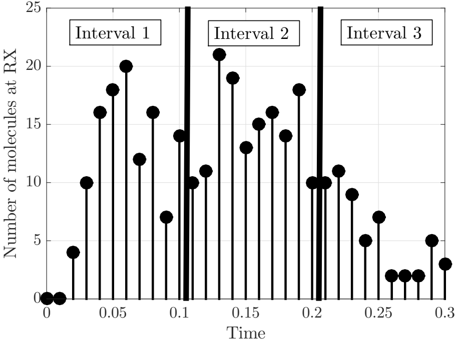
$\rightarrow$ 110 . . .

What we observe:

- Throughput
- Bit Error Rate

Detection Performance

We can improve with system memory OR modifying the channel



Noel, Cheung, Schober, *IEEE Trans. NanoBiosci.*, Sept. 2014.

Detection Performance

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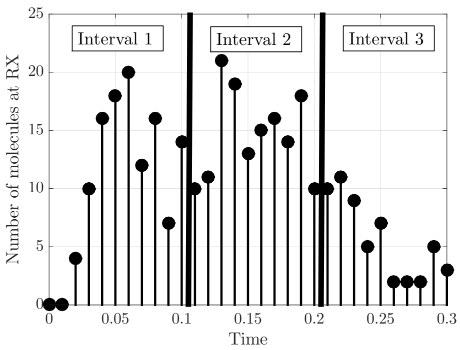

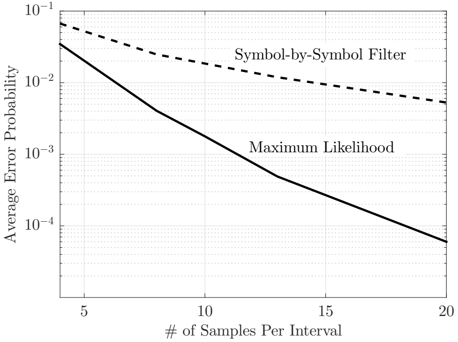

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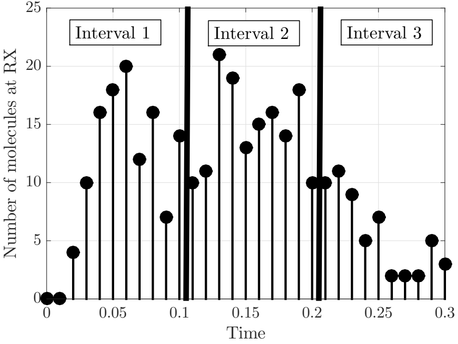
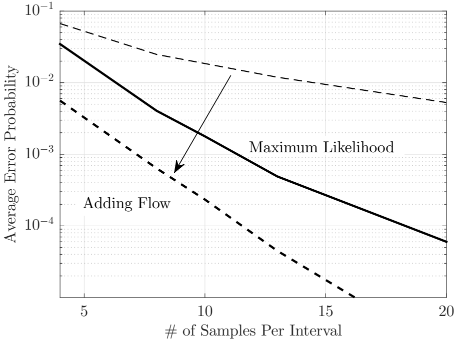




Noel, Cheung, Schober, *IEEE Trans. NanoBiosci.*, Sept. 2014.

Relaying can help you reach farther, faster[1]

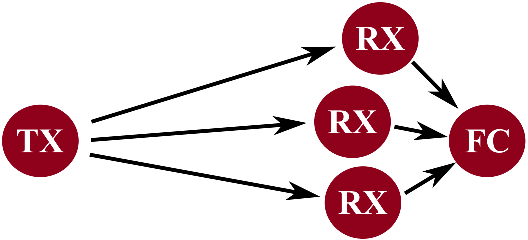
[1] Ahmadzadeh, Noel, Schober, *IEEE Trans. Mol. Biol. Multi-Scale Commun.*, Jun. 2015.

[2] Fang, Noel, Yang, Eckford, Kennedy, *IEEE Trans. Mol. Biol. Multi-Scale Commun.*, Sept. 2017

Multiple Communication Links

Relaying can help you reach farther, faster[1]

Cooperative Detection can improve reliability[2]

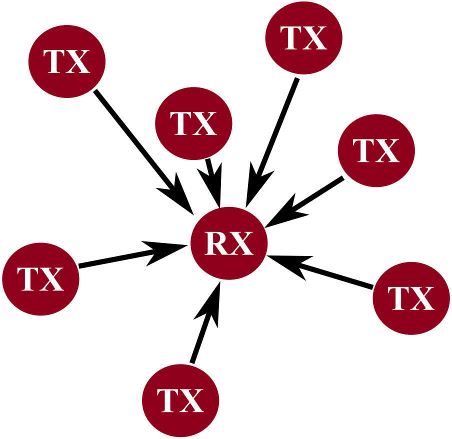


[1] Ahmadzadeh, Noel, Schober, *IEEE Trans. Mol. Biol. Multi-Scale Commun.*, Jun. 2015.

[2] Fang, Noel, Yang, Eckford, Kennedy, *IEEE Trans. Mol. Biol. Multi-Scale Commun.*, Sept. 2017

Other Communications Results

Very Large Networks[1]



[1] Deng, Noel, Guo, Nallanathan, Elkashlan, *IEEE Trans. Mol. Biol. Multi-Scale Commun.*, Jun. 2017

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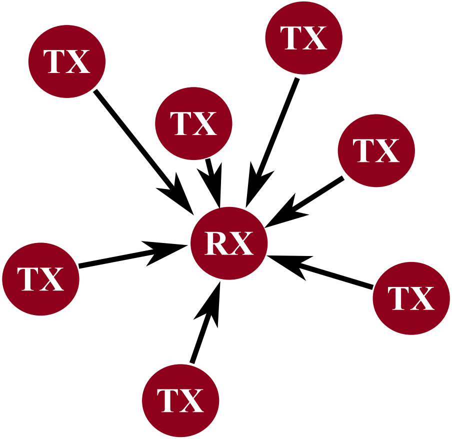
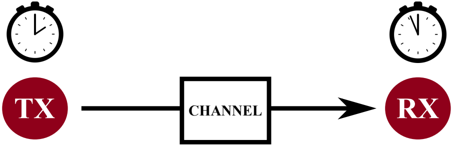


Asynchronous Communication[2]



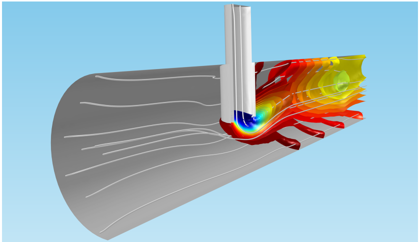
[1] Deng, Noel, Guo, Nallanathan, Elkashlan, *IEEE Trans. Mol. Biol. Multi-Scale Commun.*, Jun. 2017

[2] Noel and Eckford, *Proc. IEEE ICC*, May 2017

1. **Background (20 min)**
   - Communications Engineering and Networks
   - Nanonetworking and Molecular Communication
   - Applications
2. **Communications Modeling and Analysis (15 min)**
   - Micro/Nano Channel Modeling
   - Communications and Networking Solutions
3. **Biophysical Signal Propagation (10 min)**
   - Simulation Tools
   - Behavioral Dynamics
   - Information Transfer
4. **Conclusions**

Popular Generic Simulators

Sample Commercial Platforms



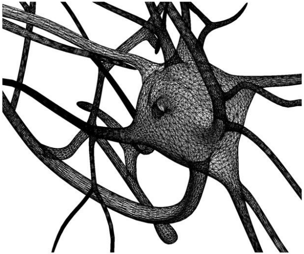
COMSOL Multiphysics (Continuum)[1]

ANSYS (Continuum)[2]

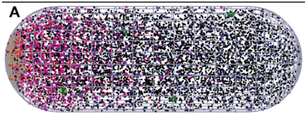
Images: [1]https://uk.comsol.com/multiphysics/what-is-mass-transfer
[2]https://www.ansys.com/products/fluids

Popular Generic Simulators

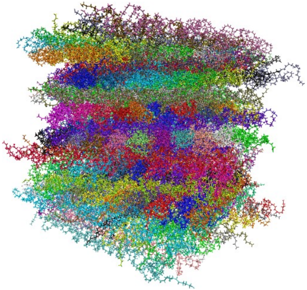
Sample Open Source Platforms



URDME (Mesoscopic)[1]



Smoldyn (Microscopic)[2]

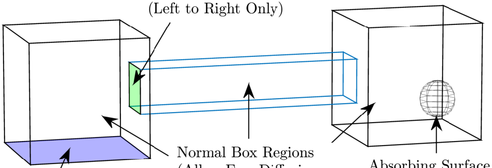


LAMMPS (Mol. Dynamics)[3]

Images: [1]https://doi.org/10.1186/1752-0509-6-76, [2]https://doi.org/10.1371/journal.pcbi.1000705, [3]https://lammps.sandia.gov/prepost.html

AcCoRD

Actor-based Communication via Reaction-Diffusion



- Written in C with utilities in MATLAB
- “Sandbox” environment design
- Chemical reactions, flow, surfaces, membranes, data modulation
- MATLAB utilities for making videos and plots
- Public website with user manual available

Image: Noel, Cheung, Schober, Makrakis, Hafid, *Nano Commun. Networks*, Mar. 2017

Software: www.warwick.ac.uk/adamnoel/software/accord/

Sandbox Environment Design with AcCoRD

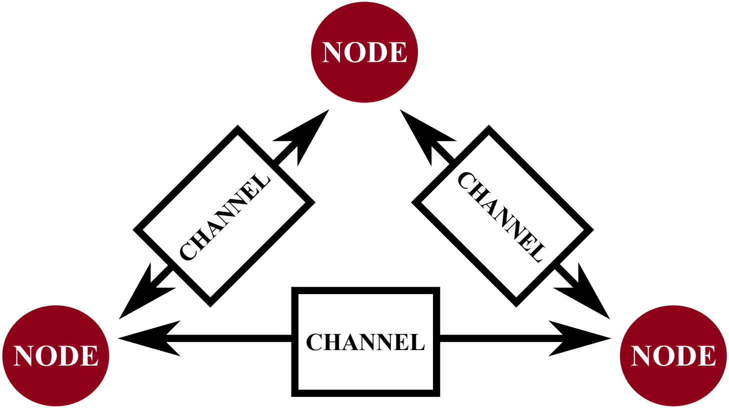
AcCoRD: Actor-Based Communication via Reaction-Diffusion

`https://www.youtube.com/watch?v=xOGkKG8PsCE`

Noel, Cheung, Schober, Makrakis, Hafid, *Nano Commun. Networks*, Mar. 2017

Software: `www.warwick.ac.uk/adamnoel/software/accord/`

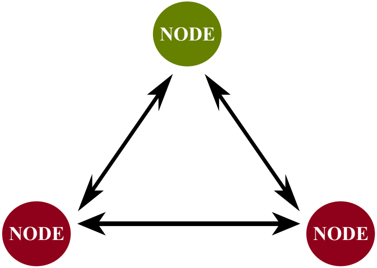
Transceiver Behavior



Behavioral Communication Problems

Devices may not always behave the way we expect them to

Cooperation vs. Competition



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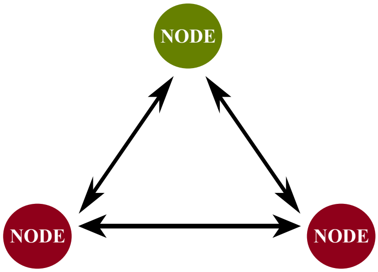
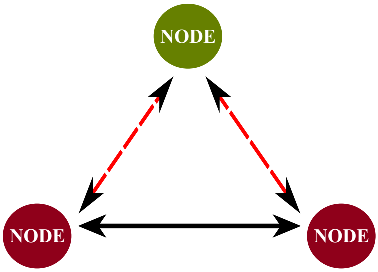
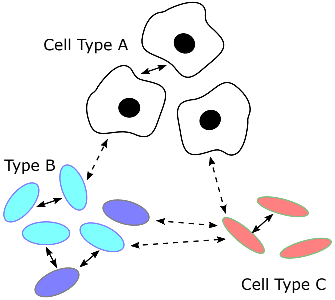


System Security



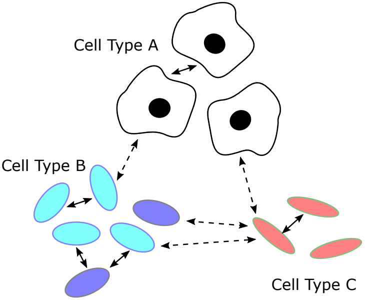
Heterogeneous Quorum Sensing



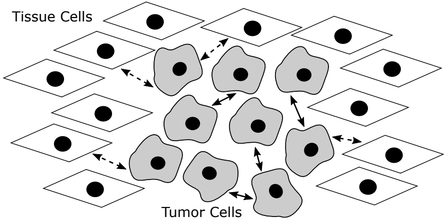
Noel, Fang, Yang, Makrakis, Eckford, arXiv

Behavior in Microscopic Cellular Populations

Heterogeneous Quorum Sensing



Tumor Growth and Development



Noel, Fang, Yang, Makrakis, Eckford, arXiv

Behavior in Microscopic Cellular Populations

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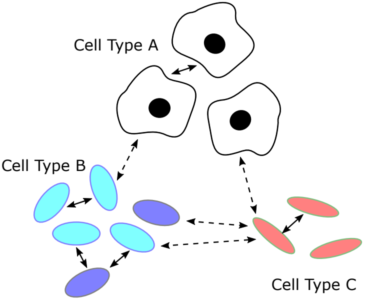

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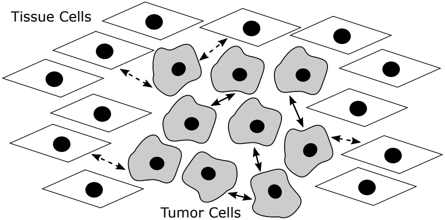

The Idea

Noisy signaling contributes uncertainty for us to mitigate or enhance

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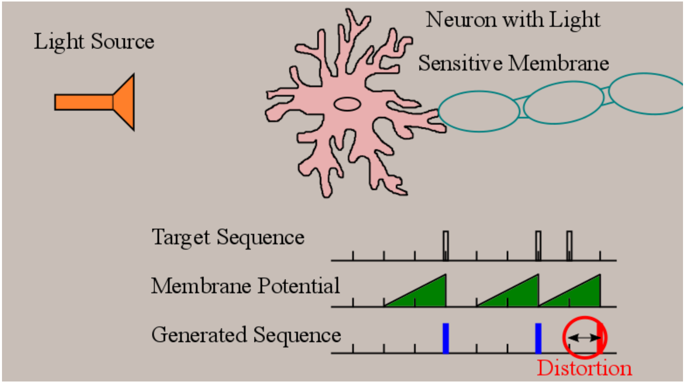
Noel, Fang, Yang, Makrakis, Eckford, arXiv

Information Theory in Biochemical Processes

How much information is there?



- **Optogenetics** lets us externally stimulate neurons
- What are the limits to generate **any kind of spike train**?
- We are constrained by a neuron's membrane potential dynamics

Noel, Makrakis, Eckford, *IEEE Trans. Biomed. Eng.*, in press

Conclusions

Nanonetworks connect devices over very small physical scales

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Conventional communication methods can be adapted to model nanonetworks

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Conventional communication methods can be adapted to model nanonetworks

Going Forward

Incredibly broad potential applications (health, environment, manufacturing)

The End

Thank you for your time and attention!

Homepage: `www.warwick.ac.uk/adamnoel`